KRYOLENS – Cryogenic Air Energy Storage

ETIP SNET Regional Workshop

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Kryolens – Project Overview

R&D project:  
„Kryolens“ – Kryo gene Luftenergiespeicherung (Cryogenic air energy storage)

Timeline:  
October 1st 2016 until September 30th 2019

Partners:  
- Mitsubishi Hitachi Power Systems Europe GmbH
- Linde AG
- Ruhr-University Bochum with the following chairs
  - Energy plant technology (LEAT), Thermodynamics (TH),
  - Thermal Turbomachines (TTM) and Energy systems and energy economics (LEE)
- RWE Power AG
- Uniper Technologies GmbH
- Lausitzer Energie Kraftwerke AG (LEAG)

Funding:  
Federal Ministry for Economics Affairs and Energy (FKZ 03ET7068)

Financing:  
2,8 m€ overall project budget incl. 57 % net public funding and 4 % external funding by LEAG, RWE and Uniper

Targets:  
Increase technology readiness level by process and component optimisation as well as determination of the technology’s techno-economic potential
LAES (Liquid Air Energy Storage) - Principle & main advantages

- No geologic limitations
- No social and ecological issues
- Flexibility and scalability
- Efficiency up to 75%*
- Based on mature technology
- Realization time < 3 years

*Definition of efficiency, please see backup slides
Mapping of Energy Storage Technologies

Source: U.S. Energy Information Administration, based on Energy Storage Association

Chemical Storage

LAES

Better for energy management

Better for power quality management

High Power Capacitors

High Energy Capacitors

Long Duration Flywheels

Batteries

Compressed Air

Pumped Storage

Hydro

High Power Flywheels

Superconducting Magnetic Storage

kW  MW  Capacity  GW

Discharge Time

Day  Hour  Second
Integration Capabilities of LAES

- Peak shaving from RES to avoid curtailment
- Utilization of LNG regasification cold to avoid cold storage in LAES system
- Ancillary services, Voltage support, energy trading, minimize grid expansion
- District heating and cooling
- Utilization of industrial waste heat, supply of cold, utilization and supply of pressurized air
- Flexibilization of conventional power plants
## Research Project - Content

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### Milestones

**MS 1**  
State of the art imaged; Most promising markets defined; Revenue potential of SOTA determined

**MS 2**  
Preferred process variants defined; First economic assessment finished; Technical potential of core components defined; Process calculation for basis processes finished; Design and order of cold storage test facility finished

**MS 3**  
Conceptual design of core components finished; Experimental investigations finished

**MS 4**  
Balance of plant and operational behaviour analysed; Economic assessment finished; Overall assessment available
AP 2: Process Analysis

Definition of preferred Process Variants – Flex-LAES

Priority 1: Flex-LAES
- Flexibilisation of existing and new power plant
- Time shifted power generation
- Peak power supply

(coal-fired) Power Plant

Air heating with steam (PP max. load / LAES discharging)

LP Pre-Heating Bypass

Compression heat for feed-water pre-heating (PP min. load / LAES charging)

LAES Discharging

Cold Storage

LAIR Storage

LP Pre-Heating

HP Pre-Heating

LAES Charging

Power out

m const.

G

Power in

M

Coal-fired Power Plant

Air heating with steam (PP max. load / LAES discharging)

Compression heat for feed-water pre-heating (PP min. load / LAES charging)

LAES Discharging

Cold Storage

LAIR Storage

LP Pre-Heating Bypass

HP Pre-Heating

Power out

m const.

G

Power in

M
Flex-LAES: Efficiency & Load Range for PCPP + LAES

Combined Powering PCPP + LAES

Steam Cycle

Additional power in combined operation of PCPP and LAES system

Time Shifted Power Generation

Reduced minimum Load of PCPP

$\eta_{\text{Net}} [-]$

$P_{\text{Net}} [\text{MW}]$

0,5

0,4

0,3

0,2

0,1

0 200 400 600 800 900
AP 2: Process Analysis

Definition of preferred Process Variants – A-LAES

Priority 2: Adiabatic-LAES

- Power-to-Power storage
- No external heat or fuel use
- Comparability with batteries
AP 2: Process Analysis

Definition of preferred Process Variants – Fuel-LAES

Priority 3: Fuel-LAES

- Hybrid storage (with fuel use)
- High efficiency and energy density
- Development of turbomaschinery (derived from GT)
AP 2: Process Analysis

Definition of preferred Process Variants – Industry-LAES

Priority 4: Industry-LAES
/LNG-LAES

- High potential of efficiency increase (use of waste heat and cold)
- LNG cold could replace cold storage
- Limited availability of heat and cold
- Not site independent

Intercooled air-compression

External heat from industrial process

External cold from LNG regasification

Power in

Power out

Liquefaction

Evaporator

Multi-stage air expander

Heat storage (optional)

Cold storage

Liq. air pump

Liquefaction

Evaporator

Multi-stage air expander

Exh. air

G

Power out

Priorities:

- Industry-LAES
- LNG-LAES
Keynotes

■ Main lessons learned and barriers to innovation deployment:
  ■ Flexibility of Flex-LAES (start-up time) need to be increased because fast reacting short term storage is most important for power plant utilities
  ■ Solid bed cold storage can significantly increase the efficiency of the process
  ■ Cost reduction necessary to compete with alternative storage technologies

■ The next project steps:
  ■ Identification of most relevant process sub-variants
  ■ Detailed component design for Flex-LAES and A-LAES
  ■ Identify cost reduction potential

■ Needs for future R&I activities coming out of the project:
  ■ Small scale pilot plant to prove technical feasibility

■ Deployment prospects of the most promising solutions.
  ■ Flex-LAES to improve flexibility of power plants in Western Europe (hard coal and lignite)
  ■ A-LAES as alternative to large scale batteries in island grids
Power for a Brighter Future
Thank You
Backup Slides
### AP 2: Process Analysis

**Process calculations ofFlex-LAES and A-LAES (LEAT)**

- Reference power plant for thermal calculations of **Flex-LAES** process is conceptual study of the reference power plant NRW (RKW NRW) from 2004
- Investigation of different integration points (charging and discharging)
- → 2 process variants defined for detailed analysis

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**Influence of different heat transfer fluids on efficiency of A-LAES process:**

- Different heat transfer fluids and heat storage fluids under investigation for **A-LAES**
- 7 process variants identified for further investigation
AP 3: Component Analysis
Hot plant section – heat exchanger (MHPSE)

Design, construction and arrangement planning for heat exchanger of the hot plant section

Example:
- arrangement planning for A-LAES gas liquid heat exchanger

- Modular construction → quick adjustment to size requirements

Optimisation of component parameters and materials for cost reduction and efficiency improvement
AP 3: Component Analysis
Storage Materials for Packed Bed Cold Storages (RUB–TH)

- **Storage mass and cylinder volume**
  - Material price, storage mass and cylinder volume are economic indicators of the packed bed cold storage

- **Analysis of storage efficiency and material properties:**

- **Analysis of storage materials**
  - Nine materials are investigated
  - Lead yields the best storage efficiency $\eta$
  - PP, PE, NaCl and quartz yield the best compromise of feasibility and economy
AP 3: Component Analysis
Market Screening for adiabatic Compressors for A-LAES (TTM)

- Example: adiabatic axial compressor (Siemens) with $T_{\text{max,compression}} = 350 \, ^\circ\text{C}$

- Example: Aero derivative gas turbine GE LMS 6000 with $T_{\text{max,compression}} = 625 \, ^\circ\text{C}$

- Compression end temperature of 350°C with state of the art compressors available
- Higher temperatures up to 625°C (aero derivative gas turbines with $\pi=34$) by using axial compressors and gas turbine technology (high temperature materials)

source: Siemens AG

source: General Electric
AP 4: Economic Analysis

Benchmark PV+A-LAES vs. CSP+TES and Life Cycle Approach (LEE)

- Investigation of CSP+TES projects worldwide for definition of: techno-economic parameters of CSP plants
- Definition of A-LAES size (input for process and component analysis AP2/AP3): 50MW, 350MWh
- Investigation of relevant CSP and PV markets
- Definition of suitable CSP projects for benchmark dependent on: technical parameters, market attractiveness and solar radiation

- Consideration of whole life cycle (manufacturing, use phase, disposal)
- Comparison of resources and emissions with other storage technologies and power plants

source: J. Röder
Advantages of LAES

- Based on mature technology
- No geologic limitations
- No social & ecological issues
- Efficiency of up to 75%
- Long lifetime
- Realization time < 3 years
- Flexibility, scalability
Known ES technologies face severe limitations – A one-fits-all solution is out of sight

- **Batteries**
  - Limited lifetime
  - High storage capacity costs
  - Disposal

- **Pumped Hydro**
  - Need mountains
  - Social, environmental issues
  - Long realization time

- **Compressed Air**
  - Need salt dome
  - Long realization time

- **Flywheels, Capacitors**
  - Short duration of storage
  - High storage capacity costs
LAES – Fact Sheet

- Energy Density: 70 – 100 kWh/m³
- Power output: 10 – 600 MW
- Storage Capacity: > 1000 MWh
- Discharging duration: 2 – 12 h
- Efficiency: 50 – 65 %
  (>65 % by utilizing waste heat)
- Lifetime: 20 – 30 years

Pictures:
1) 3D plot of LAES power recovery unit (MHPSE)
2) Cryogenic storage tank 1600 m³ (Source: The Linde Group)
LAES - Comparison to CAES

<table>
<thead>
<tr>
<th></th>
<th>Huntorf CAES</th>
<th>McIntosh CAES</th>
<th>GT-LAES Technology (4h dis.) (H25(32) / H80 / M501JAC)</th>
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<tbody>
<tr>
<td>Capacity, MWh</td>
<td>480</td>
<td>1060</td>
<td>304 / 1004 / 2564 *</td>
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<tr>
<td>Power-Output, MW</td>
<td>321</td>
<td>110</td>
<td>76 / 251 / 641 *</td>
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<tr>
<td>Round trip efficiency, %</td>
<td>42</td>
<td>54</td>
<td>52 / 54 / 56</td>
</tr>
<tr>
<td>Storage volume, m³</td>
<td>310 000</td>
<td>538 000</td>
<td>1 900 / 6 000 / 11 300 **</td>
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<tr>
<td>Storage density, kWh/m³</td>
<td>1.55</td>
<td>1.97</td>
<td>160 / 167 / 227</td>
</tr>
</tbody>
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Time-factor (Charging-/Discharging-time): Huntorf 4 / McIntosh 1.6 / LAES 2 (variable)

Source: The Linde Group

* GT power incl.
** LAIR
GT-LAES – Stand-alone or Retrofit based on mature Components

→ GT-LAES combines energy storage with GT peaker plant

Intercooled air-compression

Storage Input:
approx. 10 - 200 MW_{el}

Efficiency:

\[ \eta_{\text{system}} = 81 \text{–} 83\% \]
\[ \eta_{s,50\%} = 55 \text{–} 67\% \]
\[ \eta_{RT} = 52 \text{–} 56\% \]
\[ \eta_{F} = 83 \text{–} 86\% \]
\[ m_{CO2} < 240 \text{ kg/MWh}_{el} \]

Liquefaction

Cold storage

Evaporator

Liq. air pump

Storage Output (Air expander):
approx. 10 - 300 MW_{el}

Heat recovery air heater

Exh. air

Power out

Gas turbine (new or retrofit)

Natural gas In

Power out

Liquefaction

Cold storage

Evaporator

Liq. air pump

Storage Output (Air expander):
approx. 10 - 300 MW_{el}

Heat recovery air heater

Exh. air

Power out

Gas turbine (new or retrofit)

Natural gas In

Power out
CO₂-Footprint of produced Electricity OCGT / CCGT / LAES

- OCGT: ~526 [kg CO₂/MWh el]
- CCGT: ~345 [kg CO₂/MWh el]
- GT-LAES: ~230 [kg CO₂/MWh el]
- adiabatic LAES (future outlook)
LAES Efficiency

System Efficiency:

\[ \eta_{\text{system}} = \frac{\text{Air Expander Output}}{\text{Compressor Input}} \]

Storage Efficiency:

\[ \eta_{s,\text{NG}}\% = \frac{\text{LAES Output} - \eta_{\text{NG}} \cdot \text{Gas Input}}{\text{Compressor Input}} \]

Round-trip Efficiency:

\[ \eta_{\text{RT}} = \frac{\text{LAES Output}}{\text{Compressor Input} + \text{Gas Input}} \]

Fuel Efficiency:

\[ \eta_{\text{F}} = \frac{\text{LAES Output}}{\text{Gas Input}} \]